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Geophysical Research Letters

RESEARCH LETTER
10.1029/2024GL111220

Climatic Controls on the Length and Shape of the World's Drainage Basins

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Key Points:

- Our near-global analysis of 254,951 basins shows climate dependence in Hack's Law
- Drainage basins are systematically longer and narrower in drier regions
- These findings suggest that arid channels extend downstream during extreme events

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Singer, M. B., Grieve, S. W. D., Chen, S.-A., & Michaelides, K. (2024). Climatic controls on the length and shape of the world's drainage basins. *Geophysical Research Letters*, *51*, e2024GL111220. https://doi.org/10.1029/2024GL111220

Received 11 JUL 2024
Accepted 30 OCT 2024

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Abstract Climate is thought to affect the structure and evolution of drainage basins, but it is not clear how climate impacts the power law scaling between channel length and drainage area. Since climate controls runoff, streamflow, and erosion regimes, we looked for dependency of drainage basin morphometrics on climate within a near-global data set. We show that increasingly arid regions have longer channels and narrower drainage basins, and power law scaling between channel length and basin area (Hack's Law) increases monotonically with aridity. We suggest these results arise due to downstream channel extension by rare large floods that erode channels into previously unchanneled terrain, yielding a morphometric signature in drylands that is preserved over long timescales due to a lack of subsequent topographic smoothing. This new understanding of drainage basin morphometrics on Earth may be used to inform interpretations of past climates on our planet and other solar system bodies.

Plain Language Summary The development and structure of river basins is of great interest to various research disciplines, and it has long been assumed that climate plays an important role in drainage basin characteristics. We leveraged a new global database of drainage basin length and shape to assess how these metrics vary with climate. We show that multiple drainage basin metrics change with the degree of aridity, suggesting that longer channels in narrower basins are more common in progressively drier regions. These results are relevant to the understanding of how rivers will respond to climate change and for interpreting drainage basin histories on other planetary bodies.

1. Introduction

Metrics of topography and topology from drainage networks provide information about the forces involved in their formation (Chen et al., 2019; Dunne, 1990; Horton, 1945; Montgomery & Dietrich, 1988, 1989; Mudd et al., 2014; Perron et al., 2012; Rinaldo et al., 1995; Seybold et al., 2017; Slater & Singer, 2013; Tucker & Bras, 1998), but there is currently a lack of systematic understanding of how climate influences drainage basin metrics. Channel length (L) is a metric of along-channel distance from source to mouth, and is fundamentally affected by channel head position (the point in the landscape at which fluvial erosion exceeds sediment input (Montgomery & Dietrich, 1988)) as well as the downstream limits on topographic channel extension. Channel head position is assumed to be approximately fixed for a stationary climate regime. For example, larger upstream drainage areas are required to incise a channel head in arid climates due to limits on the production of water (Montgomery & Dietrich, 1988). The downstream extent of channels is often controlled by the presence of downstream water bodies. Perennial river channels in humid regions typically debouch into a higher order stream, lake, sea, or ocean, while endorheic (internally draining) basins, common to drylands, are only limited in their downstream extent by the net balance of water supply from upstream required to erode the channel farther downstream. Drainage basin area (A), or area upstream of the most downstream point on a channel, reflects the topological spreading of the channel network, bifurcation frequency, and tributary junction angles (Horton, 1945; Montgomery & Dietrich, 1988; Seybold et al., 2017; Yi et al., 2018). Drainage basin shape can be expressed by the Gravelius compactness (GC) coefficient (Gravelius, 1914; Sassolas-Serrayet et al., 2018), which quantifies the elongation of the basin as the ratio between the basin perimeter and the circumference of a circle equal to the basin area, where a value of one indicates a perfectly circular basin and increasingly high values indicate progressively elongated basins (with a high length-width ratio).

The relationship between L and A is generalized regionally and across the globe by Hack's Law ($L = cA^h$), originally based on regional field surveys (Hack, 1957), where c is a coefficient and h is an exponent. Subsequent research on Hack's Law based on field surveys, maps, and topographic data has settled on a near-universal power law scaling for numerous basins, where h varies between approximately 0.5 and 0.6 (Montgomery & Dietrich, 1992; Mueller, 1972; Rigon et al., 1996; Willemin, 2000), suggesting climatic invariance. Additionally, c has been shown to correlate with GC, varying between 1 and 3 (Sassolas-Serrayet et al., 2018). Hack's Law is commonly used to characterize the emergent properties of channel networks on Earth and other planetary bodies (Rigon et al., 1996; Yi et al., 2018), to quantify hydrologic response times (Rinaldo et al., 1998), and to parameterize geomorphic landscape evolution models in order to assess the effects of tectonics and other environmental phenomena on network development (Tucker & Whipple, 2002).

We hypothesize that each of these diagnostic drainage basin morphometrics (L, A, GC) should vary across the globe, depending on the regionally relevant set of controls (climate, glacial history, tectonics, etc.) and that accordingly, Hack's Law (h and c) should exhibit climatic dependency. Climate controls the regional water cycle and its translation into streamflow generation, channel erosion regimes, and vegetative resistance, so its expression over the relevant spatial and temporal scales is likely to be a key influence on drainage network development (Chen et al., 2019; Collins & Bras, 2008; Tucker, 2004), and we should expect to see broad differences in drainage basin metrics in distinct climatic zones.

Recent research has indicated that climate controls various aspects of drainage network topography and topology (Bonnet, 2009; Chen et al., 2019; Getraer & Maloof, 2021; Rinaldo et al., 1995; Seybold et al., 2017; Slater & Singer, 2013; Solyom & Tucker, 2004; Tucker & Bras, 2000; Yi et al., 2018; Zhang et al., 2020). Collectively, these studies suggest that arid climate zones have a larger number of narrower drainage basins for a given area than humid climate zones and that the drainage area upstream of a channel head is larger for arid regions. A separate study applied across the continental USA argued that arid basins are shorter than humid regions basins and statistically self-similar (Yi et al., 2018).

However, there are two key factors that limit generalizable understanding of the impact of climate on drainage basin morphometrics, particularly L, A, and h. First, studies that use "blue lines" from existing hydrography data sets generally do not include ephemeral and intermittent channels (Chen et al., 2019; Jaeger et al., 2017; Messager et al., 2021). Therefore, these studies will tend to underestimate channel length in drylands, where channels do not contain frequent flow, possibly leading to the conclusion that channels are shorter in arid landscapes with correspondingly lower values of Hack's h (e.g., (Yi et al., 2018)). Second, even when channels have been extracted from topographic data rather than blue lines, studies investigating climatic controls have been limited to specific locations or regions where non-climatic factors (tectonics) may be a greater control on drainage basin evolution (e.g., Bhutan, (Sassolas-Serrayet et al., 2018)), limiting broader understanding of the role of climate forcing on basin morphometrics (Michaelides et al., 2022).

Therefore, there is still significant uncertainty about the role of climate on drainage morphometrics. To fill this research gap, here we investigate the influence of climate on drainage basin characteristics by leveraging an open-access database which provides morphometric measurements of 254,951 climate-classified basins and the longest river channel within them. We use this database to: (a) analyze the distribution of key basin morphometrics (L, A, GC) classified by climate and (b) characterize how Hack's h and c vary by climate regime. This near-global analysis sheds light on the systematic influence of climate on drainage basin morphometrics.

2. Methods

To investigate the influence of climate on drainage basin morphometrics over a wide range of climates, we utilized the open-access Global Drainage Basin Morphometrics database (GDBM), a data set containing drainage basin metrics for relatively small basins (<3,000 km^2) in which the longest channel resides entirely within a single Köppen-Geiger (Peel et al., 2007) climate subzone between 60°N and 56°S (Figure S1a in Supporting Information S1). A full description of the data set (Grieve et al., 2024) and sensitivity analysis is contained in the Supporting Information S1, so we provide only a brief summary here. The near-global, spatially explicit GDBM was extracted from NASA's 30-m Shuttle Radar Topography Mission Digital Elevation Model (SRTM-DEM),

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using software designed for extracting morphometrics with speed and reproducibility, and without prior assumptions about channel locations or their extent (Clubb et al., 2017; Grieve et al., 2024). The extraction procedure included masking of areas covered by major lakes (Lehner & Döll, 2004), and several validation steps to ensure the extracted database is robust and minimizes extraction of non-channel features (*Supporting Information-Summary of Global Drainage Basin Morphometrics*). The GDBM database enables: (a) analysis of *L*, *A*, and *GC* from all basins above a consistent threshold area of 22.5 km^2 sensu (Chen et al., 2019), although we also analyzed sensitivity of our results to this threshold as below and in *Supporting Information-Sensitivity Analyses* and (b) characterization of Hack's *h* and *c*, the scaling between channel length and drainage area, for a range of *A* above which Hack's *h* is not expected to vary (Willemin, 2000).

Here we interrogated GDBM to generalize about the role of climate in drainage basin evolution and to test whether climatic aridity is detectable in key basin morphometrics. Specifically, we analyzed *L*, *A*, and *GC* for each extracted basin in the GDBM, classified by climate through the Köppen-Geiger climate classification (Peel et al., 2007) (Figure S1b in Supporting Information S1) and categories of the quantitative Aridity Index (Zomer et al., 2008) (*Supporting Information-Summary of Global Drainage Basin Morphometrics*; Figure S1c in Supporting Information S1). Then we plotted *L* versus *A* for each climate class to compute *h* based on least squares regression, setting the coefficient, *c*, in Hack's Law to a value of 1.3 based on optimization with a bounded set of solutions for $1 \leq c \leq 4$ for the entire GDBM (*Supporting Information-Analysis of GDBM*). If *c* is not constrained within some reasonable bounds, *h* ends up having far higher than values reported in the literature. Consistent with previous work (Sassolas-Serrayet et al., 2018), we also investigated how *c* changes with aridity by setting *h* to a value of 0.531 based on optimization with bounded values of $0.3 \leq h \leq 0.9$. By classifying the basins by climate, and also by limiting our analysis to basins with area ≥30 km^2 and ≤3,000 km^2 (*Supporting Information-Sensitivity Analyses*), we straightforwardly constrain and explore the climatic controls on drainage basin development over two orders-of-magnitude in *A*, a range in which we can be confident of a consistent climatic signal. We treat the Aridity Index and Köppen-Geiger climate classifications independently in our analysis and pose the null hypothesis that there are no differences in morphometrics between climate categories for each.

We did not control for other natural or anthropogenic variables, which likely produce higher variability in the resulting data. Therefore, we posit that any climatic signals that arise from these morphometric data can be assumed to be strong enough to overprint the scattering effects of other variables. However, to gain further confidence in our results, we also conducted a set of sensitivity analyses by imposing a series of spatial masks on the GDBM to explore the potential roles of several other expected controls on basin morphometrics across the global land surface including tectonics, large dune fields, and past glaciation. Specifically, we investigated the impacts of including and excluding areas associated with: tectonics from a seismic hazard map (Pagani et al., 2018), past glaciations based on a vegetation map for the Last Glacial Maximum (LGM) (Ray & Adams, 2001), and major dune fields (Fookes & Lee, 2009) (*Supporting Information-Sensitivity Analyses*).

3. Results

Global medians of *L*, *A*, and *GC* in GDBM for the 254,951 channels studied here are 31.9 km, 219 km^2, and 2.384, respectively (Figure 1; Figures S3 in Supporting Information S1; Figure S4 in Supporting Information S1; Table S4 in Supporting Information S1). Investigating the climatic controls, we found *L* is similar among the four main Köppen-Geiger categories except the Arid category, which contains relatively long channels and high values of *GC* (*L* = 34.7 km, GC = 2.5; Figures 1a and 1c; Figure S3a in Supporting Information S1). In terms of the Aridity Index classification, we found that surprisingly, *L* and *GC* increase systematically with higher aridity (*L* increases from 30.4 to 39.2 km, and *GC* increases from 2.25 to 2.75 spanning Sub-humid to Hyperarid classes: Figures 1b and 1d). Furthermore, when we group the GDBM basins into conservatively defined dryland (Semi-arid, Arid, Hyperarid) versus non-dryland (Dry Subhumid, Humid) categories, we find that dryland channels are disproportionately longer (for bins of length >60 m) with higher values of *GC* (for bins of GC >2.6). This result holds despite no systematic differences in drainage basin areas between aridity classes, apart from notably larger basins in the Hyperarid Aridity Index category (Figures 1e–1f; Figures S3d in Supporting Information S1).

These findings indicate a systematic control of climate on drainage basin development in drylands, in which progressively longer channels and elongated drainage basins occur in zones of higher aridity. The results are consistent with prior observations showing that arid regions produce narrower drainage basins (Bonnet, 2009) with more acute junction angles (Seybold et al., 2017), yet it contrasts with previous research indicating that arid

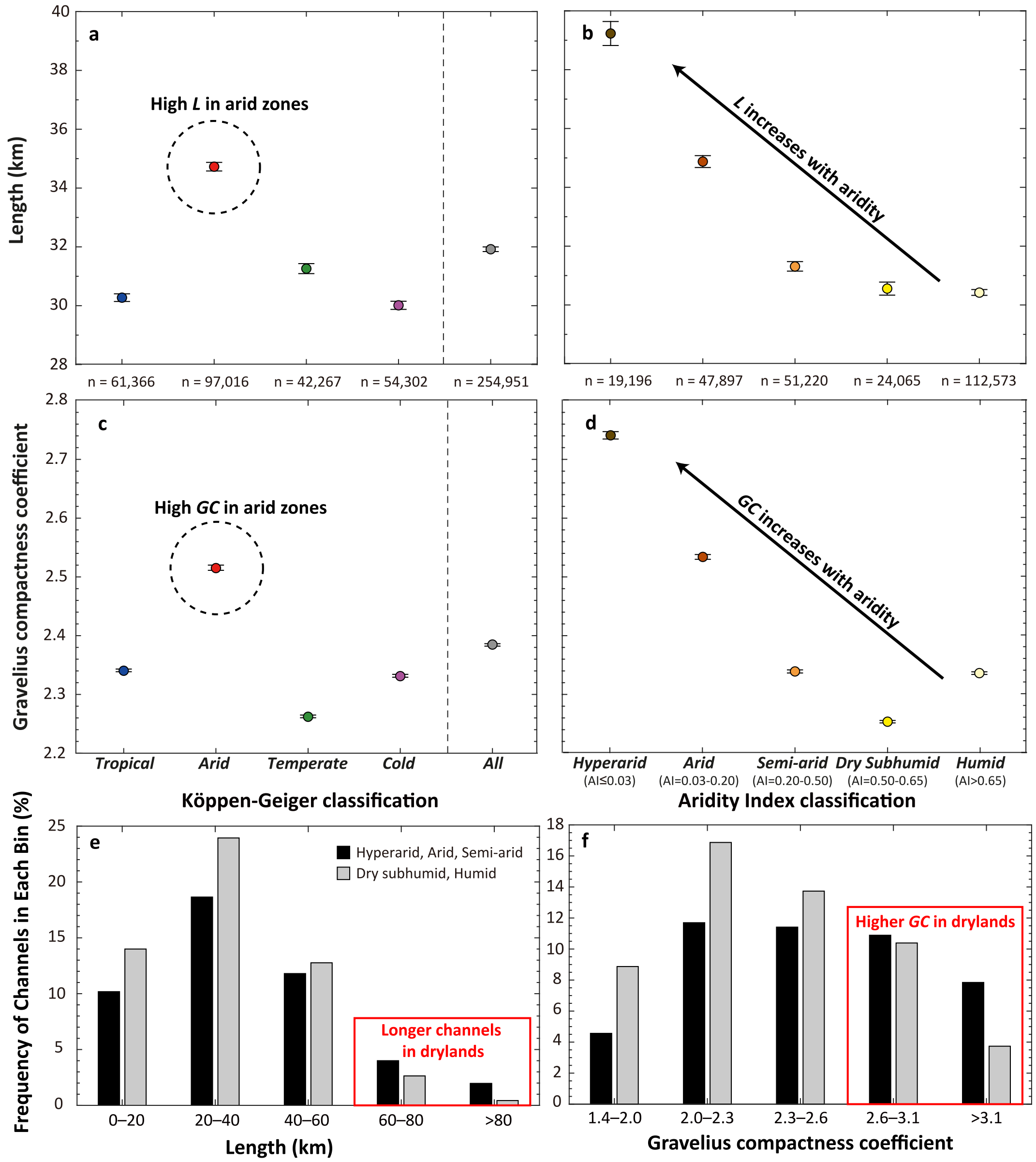

Figure 1. Morphometrics from GDBM for climate classifications. Median values of distributions by main Köppen-Geiger zone and Aridity Index classes for channel length, *L* (a, b) and *GC* (c, d). Number of basins in each climate category is contained below (a and b) Error bars in panels (a–d) represent ±2SE. Panels (e and f) show the frequency (%) of basins by bins of *L* (e) and *GC* (f), grouped by conservatively defined dryland (Hyperarid, Arid, Semi-arid) versus non-dryland (Dry Subhumid, Humid) from the Aridity Index classification.

regions have shorter channels for a given drainage area (Yi et al., 2018). It also contradicts prior work suggesting that Hack's *h* is not sensitive to climate (Sassolas-Serrayet et al., 2018).

To investigate this further, we looked for climate dependency within Hack's Law. Here we found another unprecedented result—*h* systematically increases with aridity (from 0.528 to 0.543 between Humid and Hyperarid basins, respectively, Figure 2). This result is corroborated by the fact that the Arid zone within the Köppen-Geiger classification also has the highest value of *h* of all classes (0.536; Figure S5 in Supporting Information S1). These new findings sit in stark contrast to recent work showing that Hack's *h* is systematically lower for arid basins than humid ones within the continental USA (Yi et al., 2018). However, as outlined above, the latter result may simply be a consequence of their use of a hydrography data set developed by a drainage enforcement technique, which involves burning previously mapped stream networks (blue lines) into a digital elevation model, and tends to

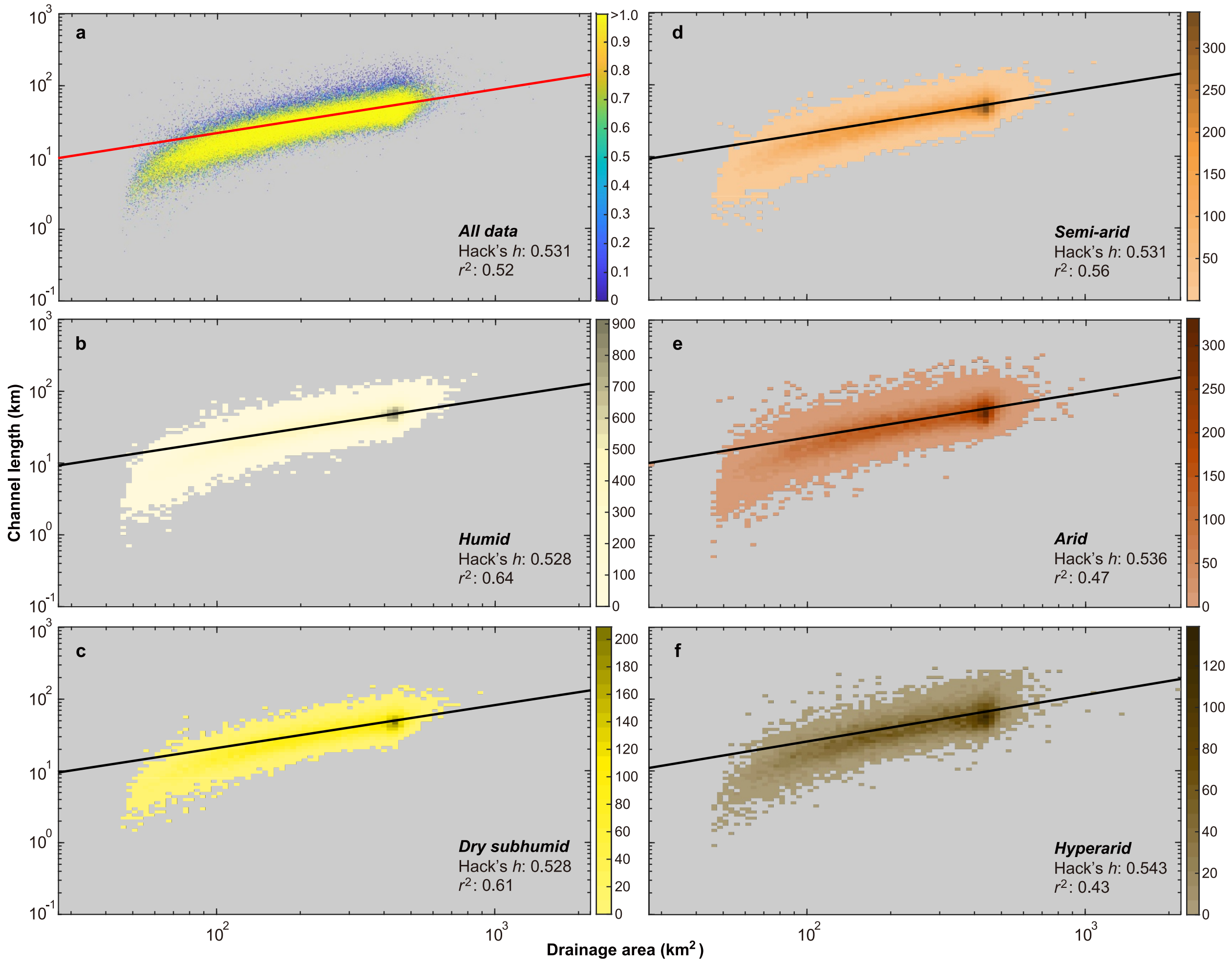

Figure 2. Climate-classified Hack's Law. Data by Aridity Index category for relationships between channel length (L) and drainage area (A). Densities of points in areas of the scatterplot are shown in the scale bars to the right of each panel. All data are shown in panel (a) The Hack exponents (h) for each panel (b–f) indicate a climatic dependency on the slope of this relationship, where increasing aridity yields a higher value of h.

underestimate river lengths within dryland regions, as arid channels flow discontinuously and less frequently (ephemeral channels) limiting their full extent on stream network maps.

Another recent study showed that Hack's h is insensitive to climate (mean annual rainfall, rather than aridity) and basin shape (Sassolas-Serrayet et al., 2018), but that study is restricted to one of the most tectonically active areas of the world (Himalayas), where tectonic forcing would overprint any climatic controls on drainage basin development (Michaelides et al., 2022; Tucker, 2004). Sassolas-Serrayet et al. (2018) also argued that the Hack's Law coefficient, c, is a more sensitive parameter that reflects basin shape and correlates with *GC*. Correspondingly, in corroboration of our Hack's h results, we also found that Hack's c monotonically increases with aridity from 1.212 (Humid) to 1.634 (Hyperarid), and is highest for the Arid Köppen-Geiger class (Figure S6 in Supporting Information S1; Figure S7 in Supporting Information S1; Table S4 in Supporting Information S1), further supporting our conclusion that basin shape becomes more elongate in drier climatic regions.

Notably, our sensitivity analyses revealed no apparent biases in the GDBM results. Specifically, we found no effects arising from three alternate channel extraction basin area thresholds (*Supporting Information-Sensitivity Analyses*), or based on including/excluding areas of the globe affected by tectonics (26% of basins in the GDBM), glacial extent at the LGM (25% of basins), or areas covered by dune fields (3% of basins). Our sensitivity analyses

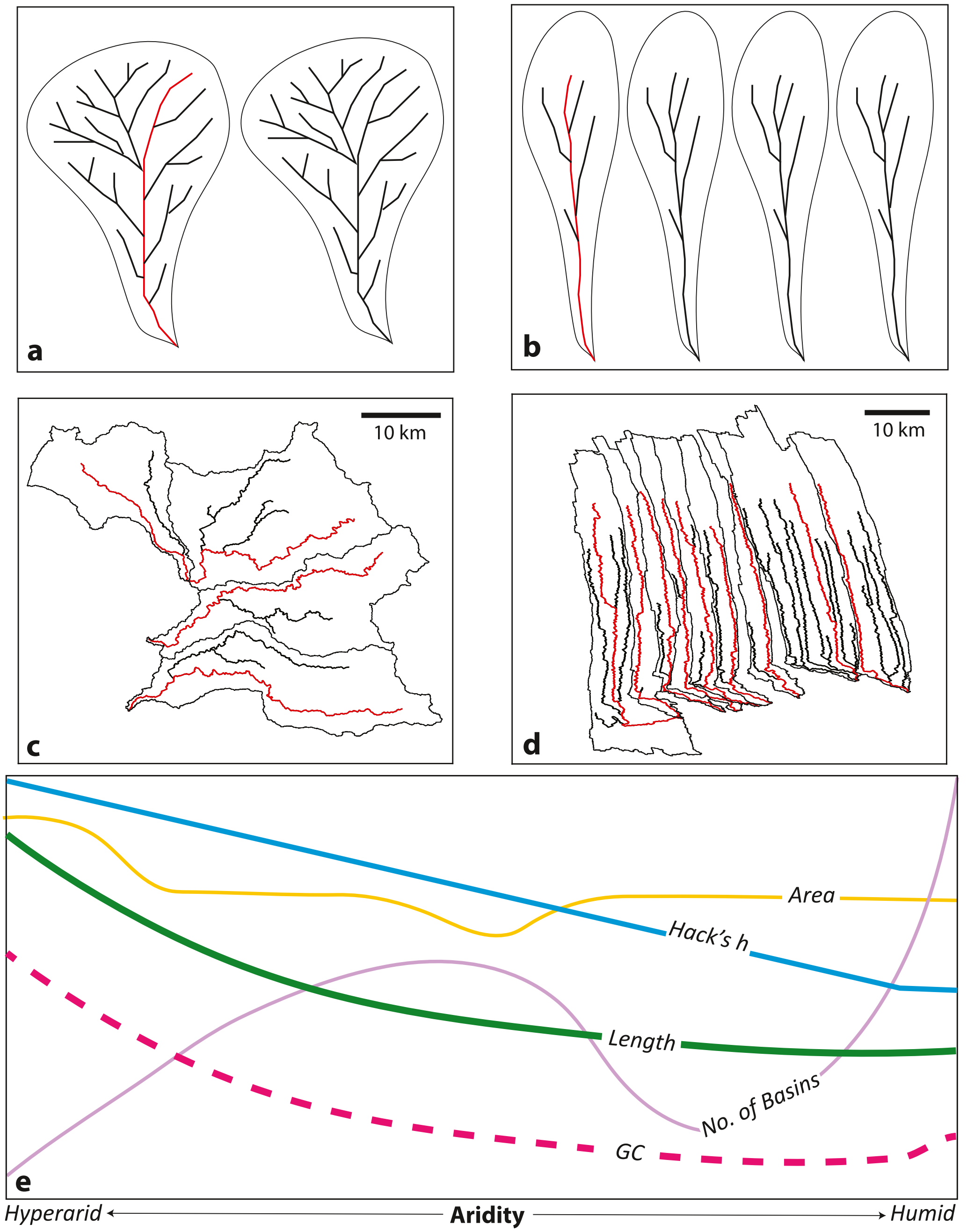

Figure 3. Climatic controls on drainage basins. Schematic of drainage basins and their river networks within humid (a) and arid (b) regions. The red trace on each plot indicates the longest (highest order) channel (mainstem). Example drainage basins of similar basin area extracted from SRTM-DEM for humid (c) and arid (d) climates in the Philippines and Australia (the area in each box corresponds to 2,900 and 4,000 km^2, respectively). Panel e summarizes how channel length, drainage area, *GC*, Hack's *h*, and number of basins vary with aridity.

confirmed the climatic dependence of *L*, *GC*, and *h* within both Aridity Index and Köppen-Geiger classifications (Table S4 in Supporting Information S1). Finally, we found the lowest drainage areas in semi-arid regions, and a characteristic climatic pattern in the number of drainage basins in the GDBM, with peaks in the Semi-arid and Humid classes (Figure 3e; Tables S1 in Supporting Information S1; Table S4 in Supporting Information S1), the latter of which is strikingly similar to the classic relationship between sediment yield and effective precipitation (Chen et al., 2021; Langbein & Schumm, 1958; Mishra et al., 2019; Walling & Kleo, 1979), suggesting a common climatic control between modern sediment yield and drainage basin formation.

4. Discussion

We view the *L*, *GC*, and Hack's *h* results (Figure 1) as near-global robust confirmation of the tendency for longer, narrow drainage basins to develop in arid climates typified by precipitation/runoff regimes that are highly variable in space and time (Bonnet, 2009; Seybold et al., 2017; Solyom & Tucker, 2004; Tucker & Bras, 2000). But by what potential mechanisms? It has been suggested that arid regions have relatively high areas of unchannelized basin due to limited runoff generation at small upland drainage areas (Montgomery & Dietrich, 1988), so we expected to find correspondingly short arid channel lengths. In fact, the GDBM data pattern is the opposite, namely higher *L* and *GC* in progressively more arid environments (Figures 1b and 1d). These results are strong evidence of a climatic control on drainage basin evolution favoring network extension (channel elongation) (Wolman & Gerson, 1978) and splitting of drainages into narrow basins in arid regions (Bonnet, 2009).

Given the obvious limitation of water in arid regions, what might explain longer channels within elongated basins? Dryland hydrology is characterized by brief spells of often intense rainfall expressed over a limited area of a basin, partial area runoff during intense rainstorms, and the development of channel flow only when the period of runoff generation is long enough (Carson & Kirkby, 1972; Michaelides et al., 2018; Singer & Michaelides, 2017). Dryland channel flow regimes are characterized by long periods of no flow, discontinuous flow along the channel, and infrequent extreme flood events that topographically reshape channels due to inherently low erosion thresholds (Singer & Michaelides, 2014; Wolman & Gerson, 1978). Channel bed erosion can occur easily in drylands, in part due to a lack of vertical sorting and channel bed armoring associated with high sediment supply during brief flood events that is incompletely sorted along the channel (Laronne et al., 1994; Singer & Michaelides, 2014). Arid basins also tend to be internally draining (endorheic), so they typically do not have a base level that is fixed by a perennial water body (larger river, lake, or sea), as is often the case in humid environments. Thus, arid channels have room to grow downstream, with a measurable topographic imprint, when the conditions are suitable.

These factors enable channel elongation by downstream extension of the arid fluvial network during rare, extreme flood events (Leopold & Miller, 1962; Rinaldo et al., 1995; Wolman & Gerson, 1978). Upstream extension of the network in drylands is unlikely due to limits on the generation of runoff capable of eroding a channel head (Montgomery & Dietrich, 1988). The topographic imprint of downstream channel extension arising from infrequent extreme events may be subsequently preserved over long timescales (Solyom & Tucker, 2004; Tucker & Bras, 2000), due to the limited effects of vegetation and bioturbation in arid regions (Rinaldo et al., 1995; Wolman & Gerson, 1978). Furthermore, arid basins tend to have limited sediment delivery from upstream that might otherwise infill the channel, smooth the topography, and obscure the signature of episodic erosion because most flood events derived from dryland rainstorms are too short-lived and spatially restricted to efficiently export sediment from upstream to downstream (Michaelides & Singer, 2014; Singer & Michaelides, 2014, 2017). Thus, we observe longer channels, higher *GC*, and higher Hack's *h* (and *c*) in progressively arid regions, even when controlling for regions dominated by tectonics, past glaciations, and dune fields (Figures 1 and 2; Table S4 in Supporting Information S1). It is very likely that these other factors do play a dominant role in affecting basin morphometrics in certain settings (Clubb et al., 2019; Hurst et al., 2019; Michaelides et al., 2022), but we find that they do not have systematic global influence that overprints the effects of climate forcing inferred by climate classifications. The general differences between humid and arid regions in terms of drainage basin morphology are summarized schematically (Figures 3a and 3b) and correspondingly for sample extracted basins in GDBM (Figures 3c and 3d), while Figure 3e shows how the key morphometrics studied here vary with aridity.

In summary, our analysis revealed clear climatic signatures within drainage basin morphometrics across the globe with and without controlling for additional interacting independent variables (e.g., tectonics or glaciation). These climate signatures can be seen in both Köppen-Geiger and Aridity Index classifications. We showed that *L*, *GC*, and Hack's *h* increase with aridity (Figures 1b, 1d–1f; Figure 2; Figure 3e). This suggests that arid basins preserve major erosion episodes and downstream extension of drainage networks, producing long, narrow basins that are closely spaced (Bonnet, 2009; Perron et al., 2009), and that the imprint of these extreme events is higher with increasing aridity (*sensu* (Rinaldo et al., 1995)). The peaks in the number of drainage basins in both Humid and Semi-arid aridity classes within GDBM (Figure 3e; Table S1 in Supporting Information S1) may indicate a bimodality in drainage basin organization due to feedbacks between climate and vegetation. It suggests that many narrow subbasins are created in semi-arid environments via network splitting (Bonnet, 2009), yielding higher sediment loads where there is enough water to erode the landscape by overland flow (Horton, 1945), but where there is not enough vegetation to resist this erosion (Collins & Bras, 2008). Once the vegetation becomes more dense in Dry Subhumid basins, the water travels along subsurface flow paths (Dunne, 1990), leading to topological spreading that further increases drainage density (Collins & Bras, 2010) and generating numerous subbasins in the well-developed drainage networks in Humid basins (Figure 3).

The morphometric patterns observed here lend strong support to the hypothesis that climate plays a fundamental role in drainage basin development, broadly corroborating evidence from previous research (Bonnet, 2009; Chen et al., 2019; Seybold et al., 2017; Solyom & Tucker, 2004). While there are numerous published examples of how drainage basin evolution is influenced by independent variables such as human impacts, tectonics, and lithology, we show that climate leaves indelible signatures within morphometrics with and without masking for these potential controls. We suggest that the influence of tectonics in active margins tends to dissipate with distance from the zone of active uplift (Michaelides et al., 2022; Whipple & Tucker, 1999), leading to clearly measurable effects of climate. These climatic signatures are detectable, irrespective of multiple confounding factors and regardless of the classification scheme used. They may provide insights into how drainage basins will evolve to climate change on Earth and into the climate history of other solar system bodies, where there are many open questions about the role of water in shaping channel systems (e.g., (Davis et al., 2016; Dickson et al., 2007)).

Data Availability Statement

All data in the manuscript and in Supporting Information S1 can be found in Grieve et al. (2024).

Acknowledgments
This research utilized Queen Mary's Apocrita HPC facility, supported by QMUL Research-IT. http://doi.org/10.5281/zenodo.438045. This work was partially supported by NSF (BCS-1660490 and EAR-1700555 to M.B.S), SERDP (RC18-1006 to M.B.S.), and NERC (NE/P015786/1 to K.M.).

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